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Using Sulfur Hexafluoride as a Gaseous Tracer To Study Ventilation Systems in Mines

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Using Sulfur Hexafluoride as a Gaseous Tracer To Study Ventilation Systems in Mines

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USING SULFUR HEXAFLUORIDE AS A GASEOUS TRACER TO STUDY VENTILATION SYSTEMS IN MINES

by

E. D. Thimons,[1] R. J. Bielicki,[1] and F. N. Kissell[2]

ABSTRACT

The Bureau of Mines found sulfur hexafluoride (SF_6), released from a lecture bottle, to be an ideal gaseous tracer for studying mine ventilation systems. Air samples were collected in glass syringes and analyzed by electron-capture gas chromatography. In these studies, the lower limit of detection was about 1 part per billion by volume (ppb) of SF_6 per part of air.

Experiments conducted in a Pennsylvania limestone mine showed this technique useful in evaluating the effectiveness of auxiliary fans, measuring low flow velocities, probing the air circulating near a working face region where ventilation appeared to be poor, and estimating volumetric flow rates in airways of large cross-sectional area and having low flow velocities. This technique was also used in a western vein-type metal mine to measure the amount of return air being recirculated into the intake air due to leakage through old stoped areas.

INTRODUCTION

Ventilation airflows in noncoal mines are generally very complex and often cannot be studied with the conventional anemometers. Multilevel workings, large airways, low air velocities, and leakage through caved areas all make it difficult to trace airflow. New procedures are needed to assess ventilation in noncoal mines and to attack such specific problems as the measurement of air exchange rates in areas of low airflow, average velocities in large low-velocity airways, recirculation, transit air time, and leakage across stoppings or air curtains. Recent research and development by the Bureau of Mines indicates that tracer gas techniques may prove useful in solving ventilation problems.

Numerous organic and inorganic materials, including radioactive substances, have been used as tracers. Most have certain inherent drawbacks. Chemical tracers are not as easily detected at low concentrations as are radioactive substances and are often highly adsorbed on many surfaces. Radioactive

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substances can be detected in low concentrations, but are difficult to handle and are likely to be unacceptable to the man working underground. An effective tracer gas must be detectable at low concentrations, safe, odorless, chemically and thermally stable, and not occur normally in the environment.

Sulfur hexafluoride meets all these essential requirements. Lester and Greenberg (8)[3] showed SF_6 to be completely safe by keeping rats in an 80 percent SF_6 atmosphere for 24 hours with no ill effects. Sulfur hexafluoride is odorless, chemically and thermally stable, and is convenient to handle and dispense in air (13). Hunt and Moore (7) showed that no measurable adsorption of SF_6 occurs on reservoir sandstone, and Whisman (14) found the same for coal. SF_6 does not occur naturally in the environment and therefore background concentration is no problem. Finally, SF_6 can be detected in very low concentrations by gas-solid chromatography, using electron-capture detection (1). Saltzman (11) and Niemeyer and McCormick (9) showed SF_6 can be traced down to a concentration of 10^{-5} ppm.

Several researchers (2-3, 13) used SF_6 in meteorological studies of moving air masses and the dispersion of airborne pollutants. Drivas (4) used SF_6 as a tracer gas to study ventilation systems in buildings. They conducted tests to measure the effectiveness of the ventilation of individual rooms and the building contamination resulting from the reentry of fume hood exhausts. SF_6 has also been used to evaluate the effectiveness of plugging oil wells to prevent wellgas from entering coal mines (10).

ANALYTICAL PROCEDURE AND TESTING TECHNIQUES

Methods of releasing SF_6 gas into the mine air were tried in the Bureau of Mines Safety Research Coal Mine at Bruceton, Pa. In these experiments SF_6 was released in the mine's only intake and the air in the lone return was sampled at a distance of about 3,100 feet from the point of release.

In the first method tried, SF_6 was released from a glass container by water displacement. A glass container of known volume was filled with pure SF_6 in the laboratory and tightly capped. In the mine, the cap was removed and the SF_6 was displaced from the container by filling it with water. Air samples taken simultaneously at different positions in a cross section of the return showed that the gas did not mix uniformly with the mine air even after traveling 3,100 feet. There was considerable variation between samples taken in the middle of the airways and about 12 inches from the roof, walls, or floor. A second indication of poor mixing was the very irregular multiple-peak curves obtained when SF_6 concentrations at the sampling point were plotted as a function of time after release. Both of these phenomena can be seen in figure 1. This can be compared with the curve shown in figure 2, where good mixing occurred. This second indication of poor mixing, multiple-peak curves, holds true only if a single airflow path exists. Where multiple airflow paths exist a series of peaks could result, but would not necessarily be an indication of poor mixing.

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

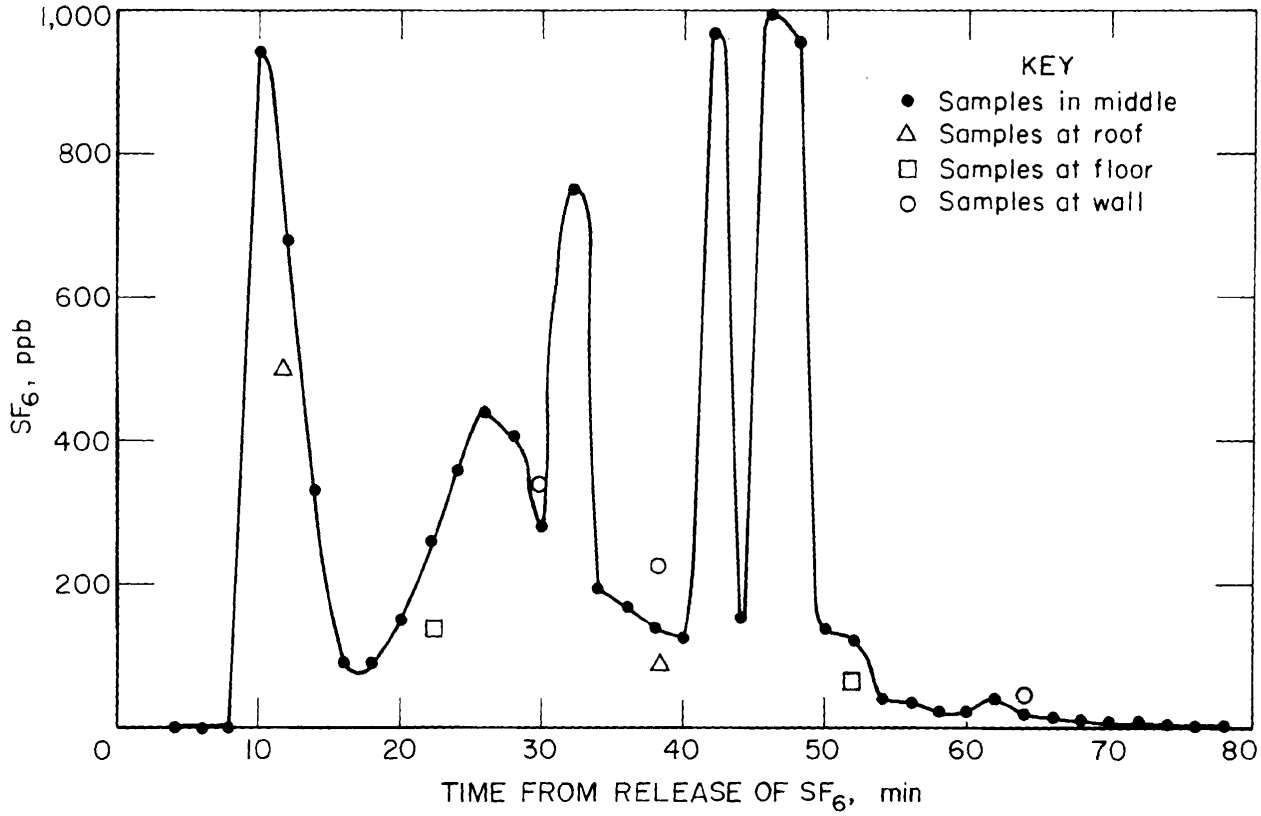

FIGURE 1. - SF_6 concentration as a function of time for a case of poor mixing.

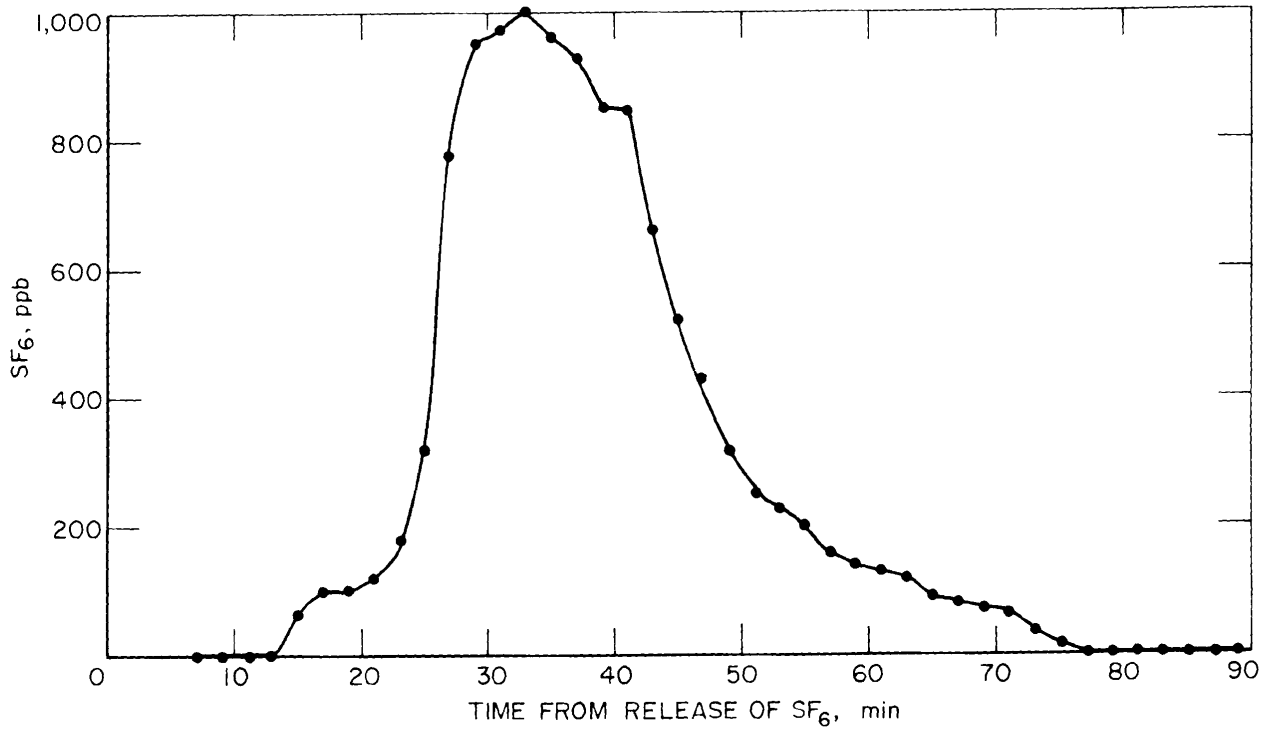

FIGURE 2. - SF_6 concentration as a function of time for a case of good mixing.

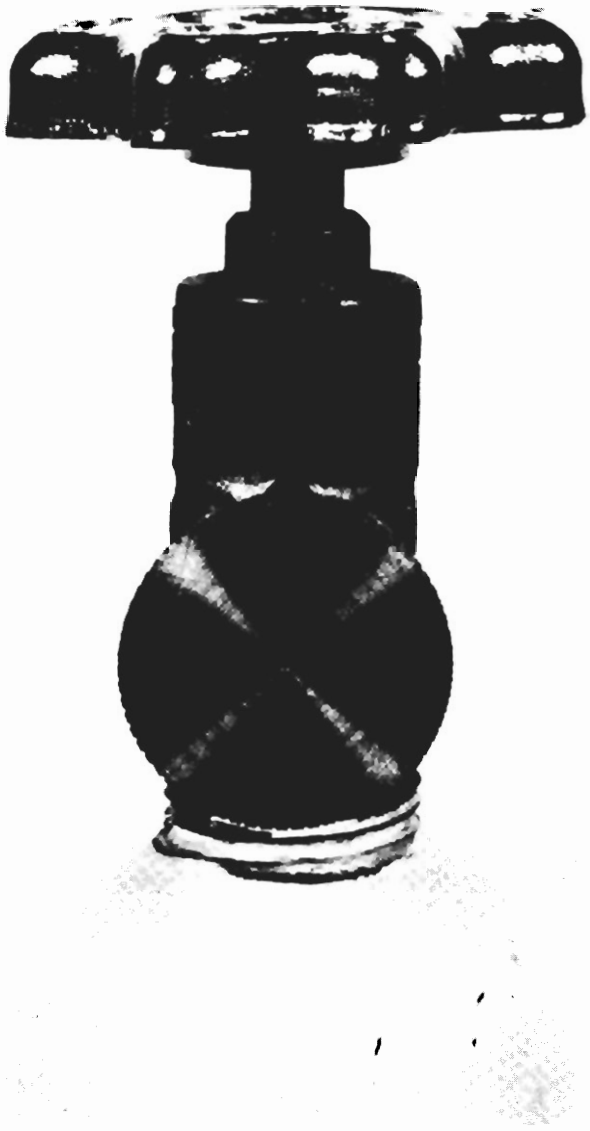

FIGURE 3. - SF_6 lecture bottle with 0.006-inch hole drilled in cap.

As a result of poor mixing, the samples taken in the center of the airway were not really representative of the average SF_6 concentration in the return. In figure 1, the amount of SF_6 released was 6 liters, whereas numerical integration of the curve data gave 8.5 liters. This is an error of about 40 percent. With good mixing, as in the test represented in figure 2, the error was seldom more than 5 percent.

Several other release methods were tried, but the problem of insufficient mixing was always present. The method that finally proved successful was to release the SF_6 directly from a SF_6 lecture bottle through a 0.006-inch hole in the lecture bottle cap (see fig. 3). The small hole resulted in a fine jet spray of the SF_6 that mixed well with the mine air. Mixing was further aided by moving the lecture bottle rapidly around the airway during release. This not only provided good mixing, but required a minimum of equipment for use underground. The amount of SF_6 released was calculated from the weight loss of the lecture bottle.

The gas samples were taken in the mine with 10-ml glass syringe bottles, tightly capped with rubber stoppers. Since several days often elapsed before the samples were analyzed and since samples were occasionally transported by plane, where they would be subjected to substantial changes in outside barometric pressure, it was important for the syringe bottles to be airtight.

Bottles that appeared to give low readings with respect to other samples were checked for leaks in the laboratory. For this purpose the bottle was filled with a known concentration of SF_6, which was rechecked after the bottle had been sealed for several days.

F. H. Shair (12) found that the surface charge on glass can yield low readings for very low SF_6 concentrations. Apparently our SF_6 concentrations were high enough to avoid this problem, but consideration is being given to the use of plastic syringes, which appear to have no surface charge and are nonbreakable.

At the sulfur hexafluoride concentrations employed (1 ppb to 1 ppm) some adsorption of the SF_6 on glass does occur. For this reason it was necessary to clean the glass sample syringes after each use by washing them in water or by flushing them with high-velocity air. Periodic spot checks of these cleaned syringes were made to insure that they contained no traces of SF_6.

The SF_6 concentration in the syringe bottles was determined with a portable electron-capture gas chromatograph. The chromatograph column was an 8.5-foot by 1/8-inch stainless steel tube packed with Chromasorb 102 (60-80 mesh),[4] which was treated at 100° C for at least 2 hours. The operating temperature of the chromatograph was 50° C. Carrier gas was argon with 5 percent methane, flowing at 10 cm^3 per 17 seconds. Samples collected in the 10-ml glass syringes were transferred to 0.5-ml syringes, from which they were injected into the chromatograph in amounts of 0.1 ml. The peak heights from the chromatograph analyses were read by a digital voltmeter and printed out at 20 voltage readings per second. The peak height for a given SF_6 sample corresponded to the highest voltage recorded for the second peak, the first peak being the air peak.

Samples were prepared in concentrations ranging from 1 ppm SF_6 down to 1 ppb SF_6. For chromatograph calibration purposes, two methods of preparation were used. The first method made use of an experimental dilution system (fig. 4) based on systems described by Saltzman (11) and Drivas (4).

To obtain a 1 ppm concentration of SF_6, 0.85 cm^3 of pure SF_6 was injected with a syringe into the large vessel, which contained air at atmospheric pressure. This vessel was then pressurized with air to 10 atmospheres. Since the large vessel had a volume of 85,000 cm^3, the resulting SF_6 concentration was 1 ppm. This vessel was used both in the exponential dilution system and in performing the daily calibration checks on the chromatograph. During months of use, the chromatographic response to this concentration was unchanged.

The operation of the exponential dilution system began with the evacuation of the entire system. The mixing chamber was filled with the prepared 1 ppm SF_6 concentration at atmospheric pressure.[5] Air was then passed through the mixing chamber at a rate that caused one complete air change in the chamber every 20 minutes. A small electric fan in the chamber insured thorough mixing. When complete mixing occurs, the SF_6 concentration follows the dilution curve given by $C = C_o e^{-N}$, where N is the number of complete air exchanges in the mixing chamber, C is the SF_6 concentration after N air exchanges, and C_o is the initial SF_6 concentration (1 ppm). To obtain a gas sample at any point in the dilution process, a syringe needle was inserted through a rubber septum on the exhaust side of the chamber. This exponential dilution process was rerun several times with better than 95-percent repeatability. Chromatograph calibration curves were developed from these results.

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[4] Reference to trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

[5] It was found that if pure SF_6 was introduced into the mixing chamber, the dilution system became contaminated by SF_6 adsorption. For this reason the dilution process was started with a concentration of 1 ppm.

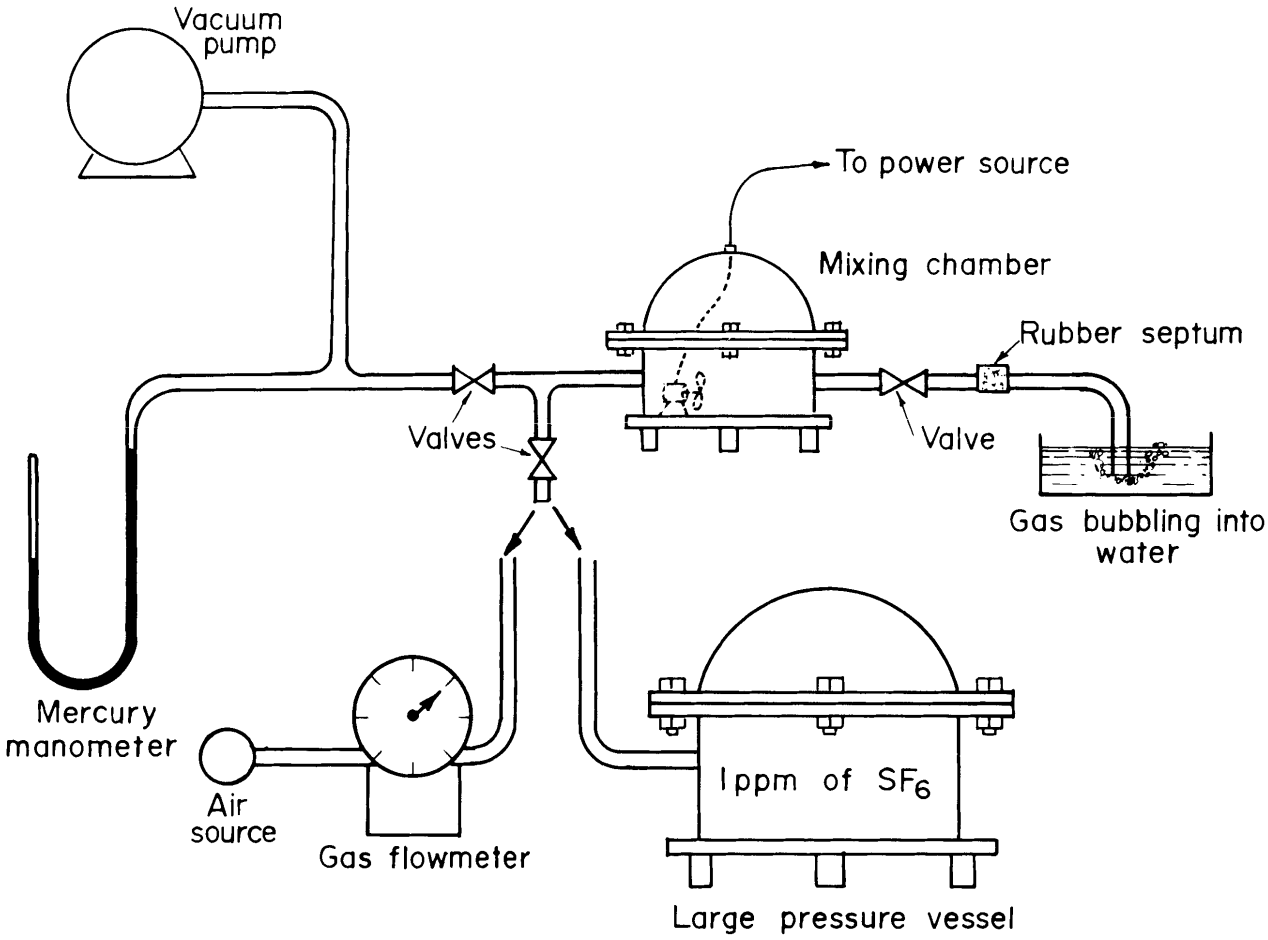

FIGURE 4. - Schematic of exponential dilution system.

The second method of obtaining calibration samples was to prepare them in rooms of known volume. This method was originally intended as a check on the results from the exponential dilution system, but proved to be just as accurate and much simpler than the dilution method. For example, to prepare a sample of concentration 100 ppb we released 9.3 cm^3 of pure SF_6 into a room having an approximate volume of 9.3×10^7 cm^3. The room air was thoroughly mixed by several fans placed around the room. Gas samples were withdrawn from the room with syringes. The only problem with this method is that the samples had to be taken in the room shortly after release, before leakage affected the SF_6 concentration of the room atmosphere. Figure 5 shows a typical curve of SF_6 concentration in a room versus time for the first 15 minutes after the SF_6 was released. The rate of decrease of SF_6 concentration varied from room to room depending upon how well the room was sealed. Samples were usually taken between 1 and 2 minutes after release of the SF_6. The difference between the chromatograph results from prepared room samples and exponential dilution samples was less than 3 percent at the same concentration level.

Figure 6 gives the chromatograph calibration curves for the ranges 10 ppb to 100 ppb and 100 ppb to 1 ppm, respectively. The peak height response is a

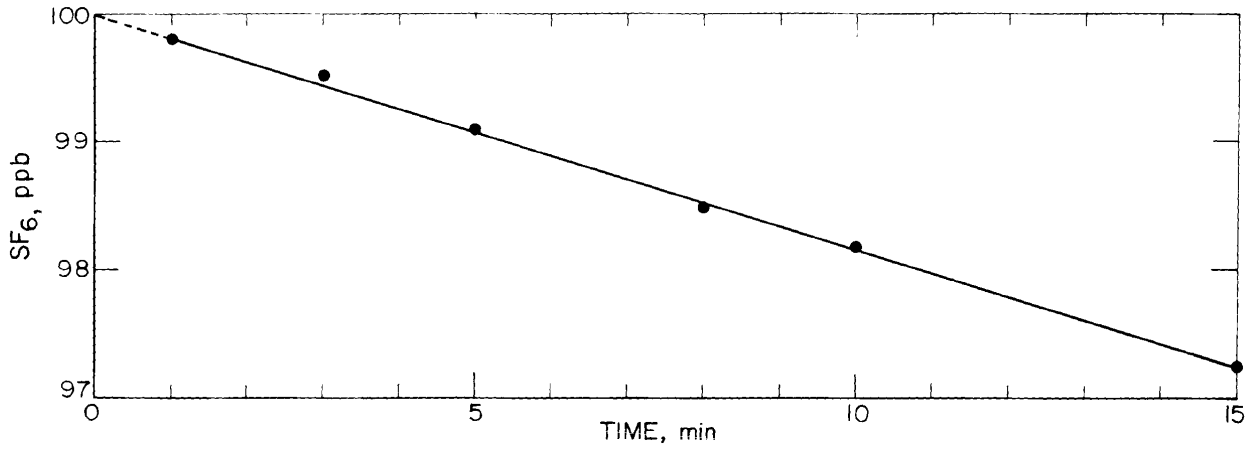

FIGURE 5. - SF_6 concentration in a room as a function of time.

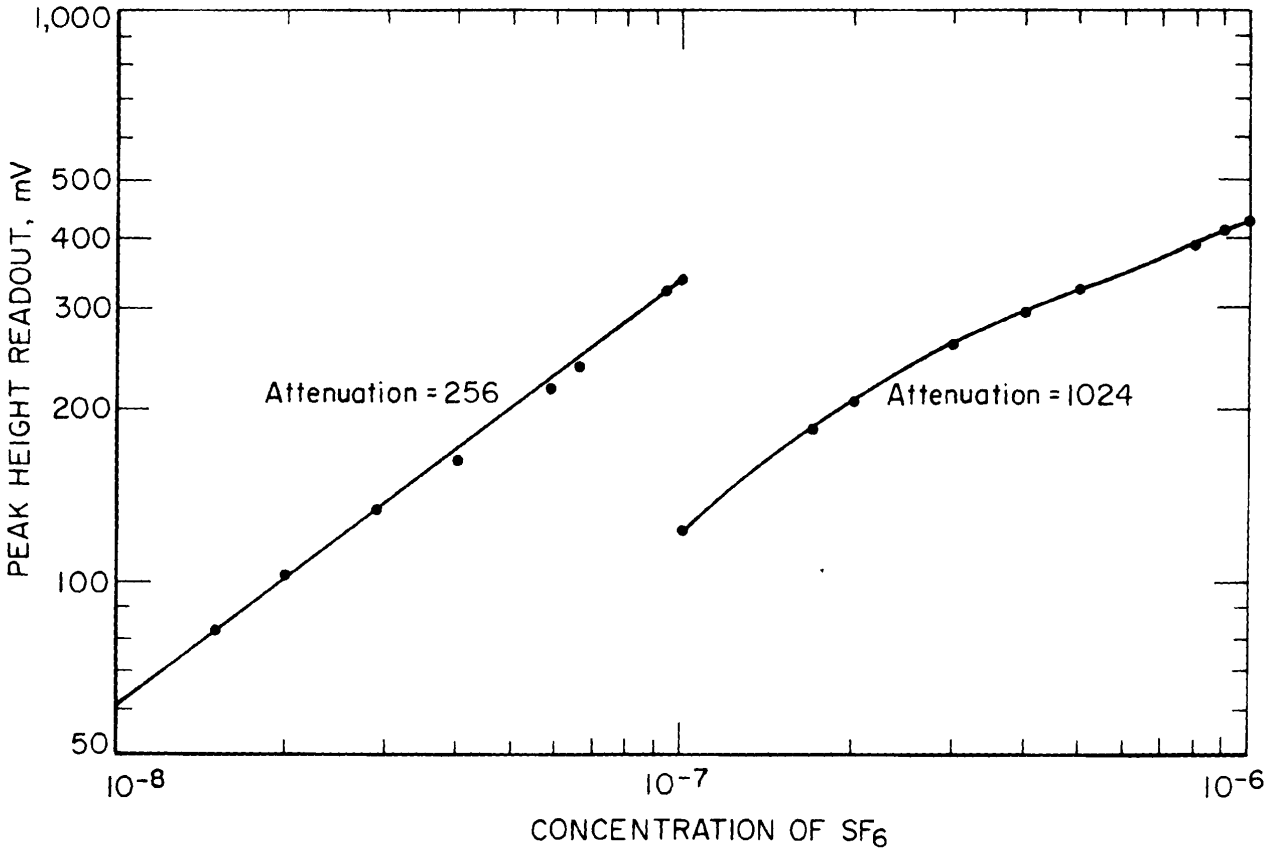

FIGURE 6. - Chromatograph calibration curves.

straight-line response from 10 ppb up to 100 ppb, but becomes nonlinear above this. Concentrations up to 100 ppb were run at attenuation 1024. It is interesting to note in figure 6 that at the change of scale concentration (10^{-7}), the attenuation apparently increases by a factor of 4 while the peak

height drops only by a factor of about 3 (from 330 mV to 120 mV). The reason for this inconsistency is uncertain, but since the calibration points were confirmed by numerous calibration samples, it appears that the cause is an inherent characteristic of the chromatograph attenuator.

PRELIMINARY SF_6 TRACER GAS TESTS IN A COAL MINE

Preliminary experiments were conducted in the Bureau of Mines Safety Research Coal Mine at Bruceton, Pa. (fig. 7), to determine how quantitatively SF_6 gas can be traced in a mine. The mine has a single intake and a single exhaust, which offered an ideal situation for testing the use of SF_6 as a tracer gas in ventilation studies. Before each trial, the airflow in the mine was measured with an anemometer traverse. The average flow is about 16,500 cfm.

The testing procedure began with the release of SF_6 into the intake air at the point labeled R in figure 6. In most experiments, SF_6 was continually released over a predetermined period of 2 to 5 minutes. This made it possible to release a fairly large volume of SF_6 without producing a concentration in the mine air higher than that for which the chromatograph was calibrated (1 ppm), and also to improve mixing of the SF_6 with the mine air. Return air

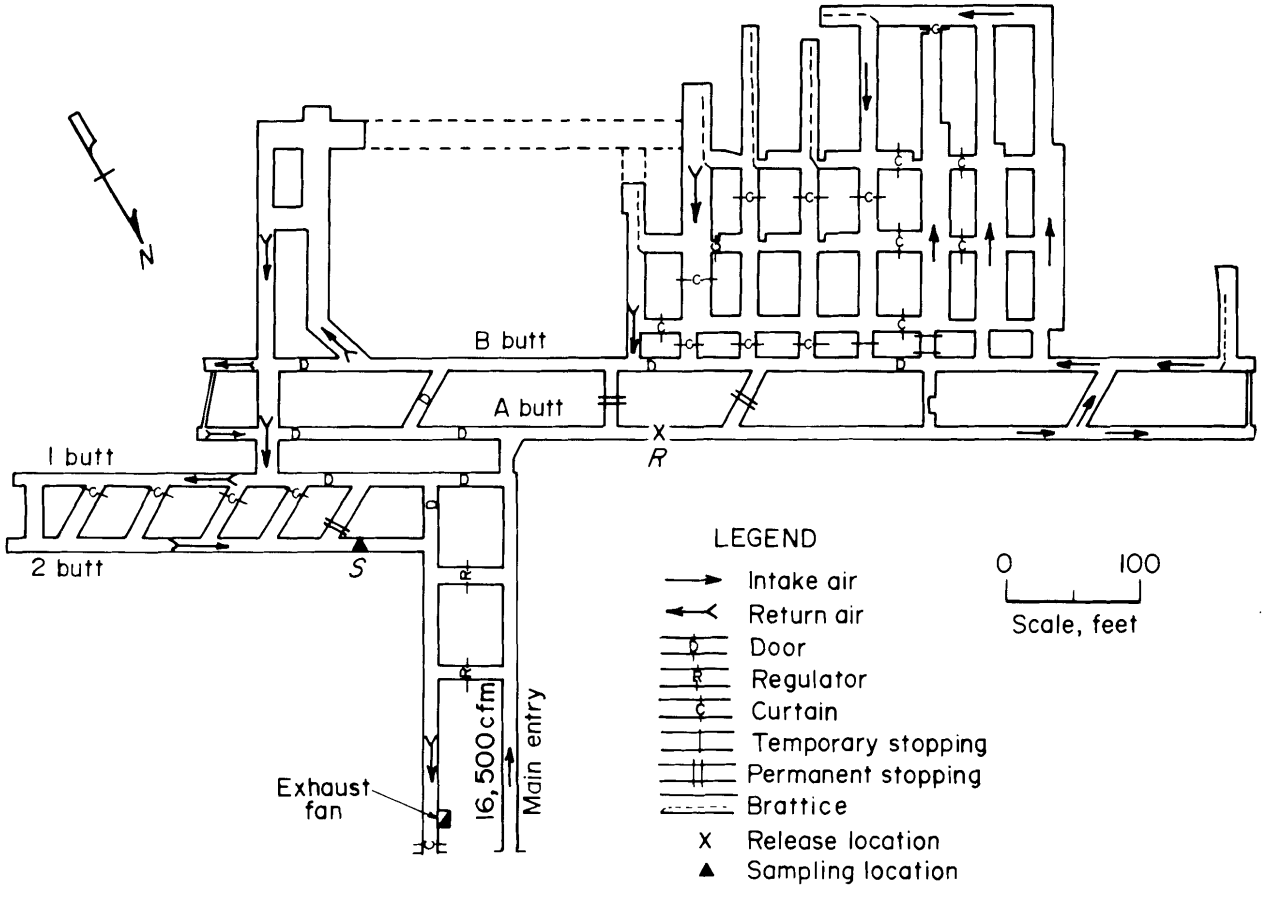

FIGURE 7. - Bureau of Mines Safety Research Coal Mine.

samples were taken every 2 minutes at position S (fig. 7) located about 3,100 feet from R. Since the maximum air velocity measured in the mine was 305 feet per minute, this meant that the SF_6 could not possibly reach the sampling location until at least 10 minutes after release, as shown in table 1. Sampling generally began 8 minutes after the release. An air sample was taken in the center of the return airway every 2 minutes, and periodically a simultaneous sample was taken near the roof, walls, or floor to check uniformity of mixing. Generally, the measurable quantities of SF_6 were exhausted past the sampling point within 90 minutes after SF_6 release ended.

Once an SF_6 release technique was found that resulted in good mixing of the SF_6 with the mine air, it was possible to release a known quantity of SF_6 into the intake air and, by numerically integrating the chromatograph results from the samples taken in the return air, account for approximately this same quantity of SF_6 in the return air (table 1). This can be done using the equation of Drivas, Simmonds, and Shair (4):

$$Q_{SF_6} = Q_{AIR} \int c\,dt.$$

Here, Q_{SF_6} is the SF_6 volume, Q_{AIR} if the volumetric airflow rate at the sampling point, and c is the SF_6 concentration at time t. Integration of this equation is simply done by multiplying C_{av}, the average SF_6 concentration in those sample bottles that contain SF_6, by the total time T during which measurable amounts of SF_6 were found in the return air. This total time T is the sampling interval (2 minutes in this case) multiplied by the number of samples with a measurable SF_6 concentration. The results of experiments in which SF_6 was released from a lecture bottle with a 0.006-inch hole in the cap are presented in table 1. An example of complete analysis of one of these tests (No. 19) is presented in the appendix.

TABLE 1. - Preliminary tracer gas test results from Safety Research Coal Mine

Test	Time from release to arrival at sample point, minutes	SF_6 released, liters	SF_6 monitored, liters	Error, percent
19	15	10.5	10.7	2
20	14	16.1	15.9	1
21	16	1.9	1.8	5

These tests showed that if the SF_6 is thoroughly mixed in the mine air, it can be quantitatively traced through the mine, thus confirming its potential value for studying underground ventilation systems.

SF_6 TRAVEL TIMES

A problem encountered in this work was to determine when to begin and end sampling. The time required for the SF_6 to initially arrive at the sampling

location and the time lapse before all the SF_6 passes this location depend on the length of travel, the air velocity, the passage of the air through stopes and cooling plants, and recirculation of the air.

Some idea of how difficult it is to estimate these travel times can be obtained from the results of several tracer gas experiments presented in table 2, which shows the expected arrival times based on velocity and distance calculations and the actual arrival times for various travel distances and conditions. It also gives the time required for SF_6 to completely pass the sampling locations in each experiment.

TABLE 2. - Comparison of estimated and actual SF_6 travel times

Distance traveled, feet	Conditions	Actual travel time (T), minutes	Expected travel time (T'), minutes	Time till last SF_6 arrived, minutes	T/T'
5,000	Straightaways and stopes.....	36	11	[1]90+	3.27
7,000	.....do.....	25	7	110	3.57
8,000	.....do.....	5	8	150	.62
6,000	.....do.....	10	4	115	2.50
8,000	Mostly straightaways	15	9	60	1.66
3,100	All straightaways...	14	12	55	1.17

[1] SF_6 still passing after 90 minutes.

The ratio of actual travel time to expected travel time (T/T') varies from 0.62 to 3.57, showing that the estimated travel times are not very accurate, especially when stopes are being ventilated. The results of table 2 suggest that it would be advisable to begin taking samples after about one-half of the estimated travel time has elapsed. It is even more difficult to decide how long to continue sampling. The only conclusion that can be drawn from the data is that it takes much longer for SF_6 to completely pass the sampling location if it travels by way of stopes.

USE OF SF_6 IN AN OPERATING LIMESTONE MINE

Several tracer gas ventilation tests using SF_6 were conducted in a single-level underground limestone mine in Pennsylvania. The general ventilation system of the mine is simple. Most of the air (about 140,000 cfm) enters the mine through an intake fan in a drift entry. The remainder enters the mine through a vertical natural draft hole from the surface. All the mine air is exhausted through a single vertical exhaust hole. Several auxiliary fans are employed in the mine to aid air movement.

The large number of intake and exhaust airways and the large cross sections of these airways (600 to 700 ft^2 average) made conventional anemometer methods of studying ventilation impractical in most areas of the mine. The air velocities were generally well below 100 ft/min; locally, air velocities were so low that even smoke clouds dissipated before traveling far enough to permit velocity estimates.

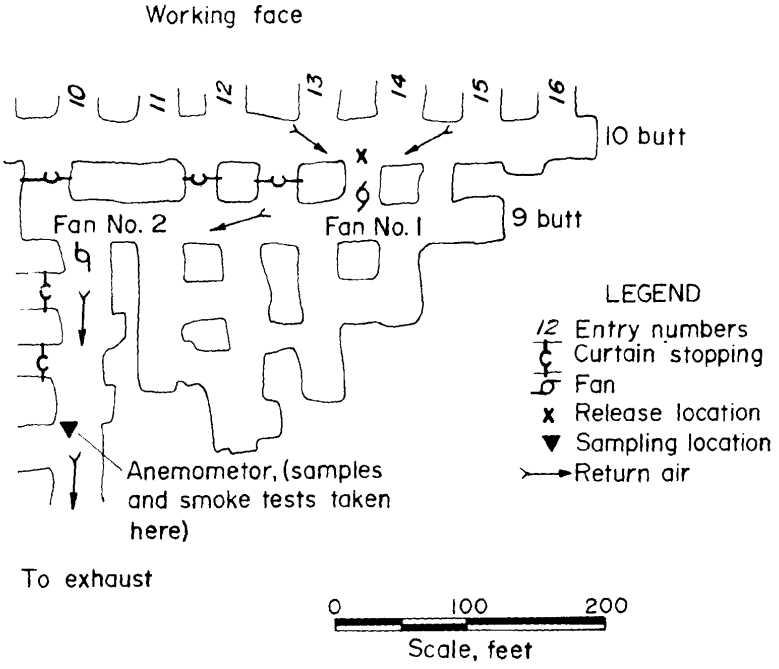

FIGURE 8. - Map showing area of auxiliary fan tests.

Six different types of ventilation experiments were conducted in this mine using the SF_6 tracer gas. They demonstrate the versatility of the tracer gas as a tool for examining underground ventilation systems.

Auxiliary Fan Tests

In an attempt to speed up the air exchange rate at the working face, two auxiliary fans were placed in the return airway leading from the working face (fig. 8). Fan No. 1 was mounted on a small platform in the center of the airway. Fan No. 2 was hung about a foot from the roof and 2 feet from the rib. No tubing was used on either of the fans. Two SF_6 tracer gas tests were run to determine if the auxiliary fans were helping tc move the air along faster or if they were just recirculating the air. The air velocity in this area, at least with the fans on, was high enough that we could check the tracer gas results against vane anemometer and smoke cloud results. The volume of air exhausted from the face was also measured.

With both fans in operation, 3.64 liters of SF_6 were released just behind fan No. 1 over the time interval from 5:12 to 5:13 p.m. Gas samples were taken every minute from 5:12 to 5:50 p.m. at the sampling location shown in figure 8.

The first detectable trace of SF_6 appeared in the sample taken at 5:16 p.m. Measurable quantities of SF_6 were monitored for 28 minutes, from 5:18 to 5:45 p.m. The average concentration of SF_6 in these 28 samples was 97.6 ppb. This information was used in the following equation of continuity:

$$Q_{SF_6} = C_{av}\ T\ Q_{AIR}, \text{ or } 3.64 \text{ liters} = \left(97.6 \times 10^{-9} \frac{ft^3\ SF_6}{ft^3\ air} \right) (28.2 \text{ liters}/ft^3)\ (28 \text{ min})\ (Q_{AIR}).$$

From this, the volume flow of air, Q_{AIR}, being exhausted from the working area past the auxiliary fans is approximately 47,000 cfm when the fans are operating. The cross-sectional area at the sampling point was about 640 ft^2, making the average calculated velocity at this location about 74 ft/min.

A smoke cloud test conducted at the sampling location gave a velocity in the center of the airway of 88 ft/min, while a vane anemometer at the same location showed a reading of 94 ft/min. SF_6 was detected in a sample taken 4 minutes after release. This means that the first SF_6 actually arrived somewhere between 3 and 4 minutes after release. Assuming that it arrived after 3.5 minutes and knowing that the total distance traveled was about 340 feet, the velocity is about 97 ft/min. This compares rather well with the velocities determined by the two other methods. Actually, the maximum velocity calculated from the SF_6 travel time should be slightly higher, because the cross-sectional area at the sampling location was, in general, a little larger than the cross-sectional areas along the path of SF_6 travel, reflecting higher velocities through smaller cross sections.

Hartman (5) shows when the Reynolds number exceeds 10,000, which is the case here, the average velocity should be 0.8 of the maximum velocity. For a maximum velocity of 97 ft/min the average velocity would be about 77 ft/min, as compared with the average velocity of 74 ft/min measured above. A summary of the results is given in table 3.

TABLE 3. - Velocity results from auxiliary fan tests

Technique	Velocity, ft/min
Anemometer (centerline velocity)	94
Smoke cloud (centerline velocity)	88
Maximum velocity from trace gas travel time	97
Average velocity from trace gas (continuity equation)	74
Average velocity (0.8 of centerline velocity)	77

The auxiliary fans were turned off at 5:53 p.m. After allowing the airflow to stabilize for 30 minutes, another 3.07 liters of SF_6 were released behind fan No. 1. Samples were again taken at 1-minute intervals at the same location as before for 50 minutes. The first sample taken showed an SF_6 concentration of 32 ppb and the concentrations of the succeeding samples varied from 20 ppb to 90 ppb for the entire 50 minutes. It was concluded that after the auxiliary fans were turned off the air in the exhaust airway began to back up slowly, so that the SF_6 sampled in the second portion of the test was the gas that had passed the sampling point in the first part of the test. An anemometer held in the center of the airway at the sampling location gave no reading, but a smoke cloud indicated a slow air movement in the reverse direction together with a great deal of erratic transverse air movement. These results show that the auxiliary fans were necessary to remove air from the working area of the mine.

Exhaust Hole Study

The entire supply of ventilation air for the mine is exhausted to the surface through a single vertical hole about 20 feet in diameter and 50 to 60 feet deep. The hole surfaces on a hillside, so that the back of the hole is 6 to 8 feet higher than the front. Often a mild wind blows across the exhaust hole from the low to the high side. This wind acted as a resisting force

against the exhausting airflow and it was possible that it could be forcing some air down the exhaust hole along the backside of the hole (fig. 9). To investigate this possibility, 17 liters of SF_6 were released around the surface perimeter of the exhaust hole over a period of 2 minutes. Starting with the time of release, gas samples were taken along the return airway every 30 seconds for a period of 15 minutes at a position about 100 feet from the bottom of the exhaust hole. After 6 minutes, some SF_6 showed up in the gas samples and continued to appear for the next 7 minutes, after which it disappeared. The presence of SF_6 underground proved that a downdraft did indeed exist in the exhaust hole, offering an undesirable resistance to the exhausting mine air.

To prevent this downdraft, a temporary brattice cloth was put up around the top front portion of the hole at a height about equal to the elevation of the backside of the hole, so that the wind would blow over top of the exhaust opening, rather than blow against the backside of the hole and force air back

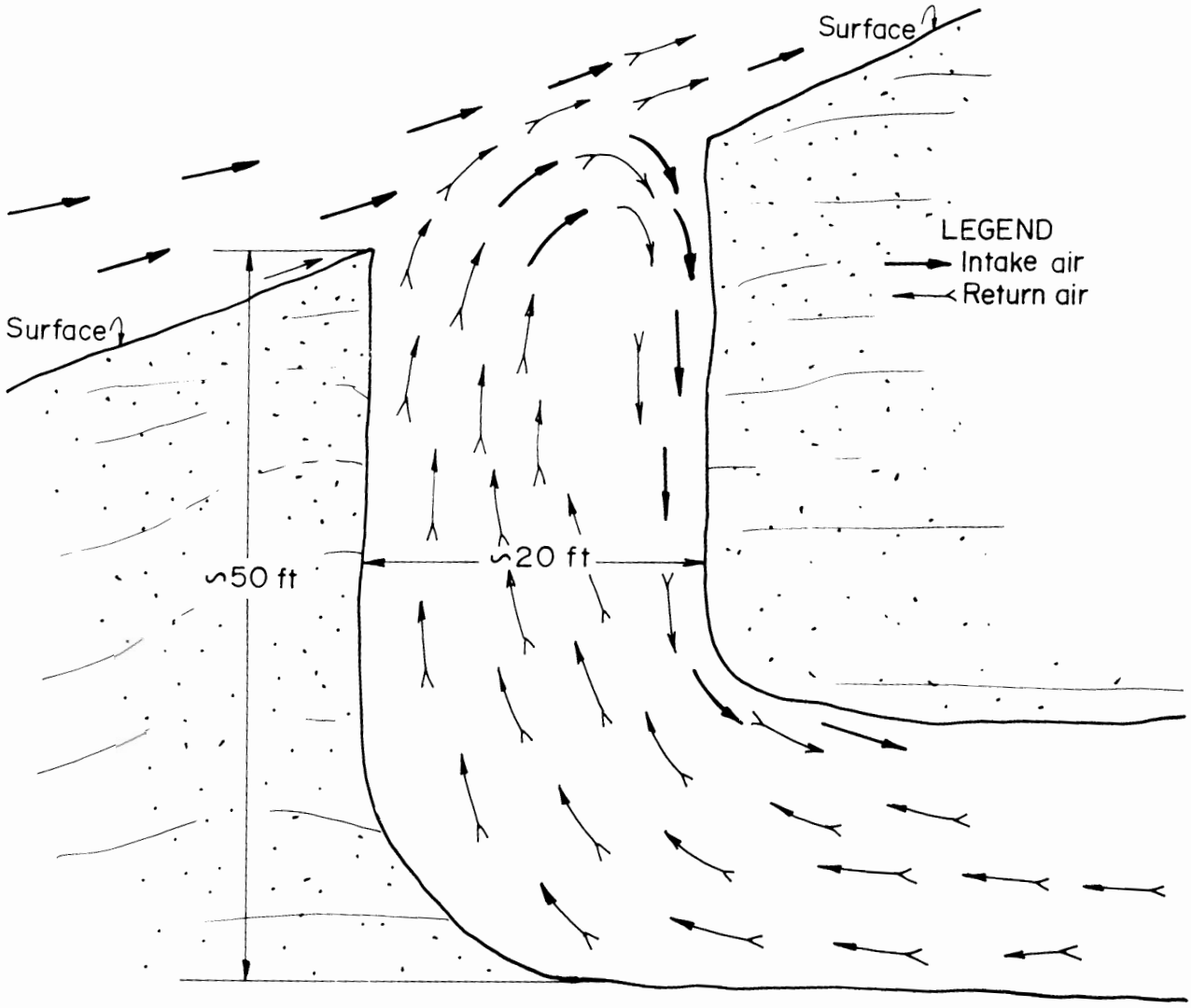

FIGURE 9. - Airflow pattern in exhaust hole.

down the exhaust. To check the effect of this brattice cloth we repeated the tracer gas test on a day when the wind was about the same as when the first test was conducted. We released 16.7 liters of SF_6 around the surface perimeter of the exhaust during a 2-minute interval and repeated the previous test. No trace of SF_6 appeared in any of the samples taken. The brattice cloth around the front portion of the exhaust hole had evidently eliminated the downdraft.

Natural Draft Intake Study

About 600 feet from the exhaust hole there is a second vertical hole to surface from an inactive area of the mine. This hole is about 70 feet deep and varies in diameter from about 16 to 20 feet. This hole was known to act as a natural draft intake, but the volume of air entering the mine through this intake was not known. As the cross section of the airway at the bottom of the hole was too large ($\simeq$ 800 ft^2) and the air velocities too low to use an anemometer traverse, the trace gas was used to measure the intake air volume.

Around the top perimeter of the hole, 12.2 liters of SF_6 were released, holding the lecture bottle of SF_6 over the intake hole and directing the jet spray into the hole to insure that all the SF_6 entered the mine. Starting at the time of release, gas samples were taken for 35 minutes at a location about 70 feet from the bottom of the hole along the intake airway. Twenty-seven of the samples contained SF_6. The average concentration was 470 ppb. Assuming that all the SF_6 released (12.2 liters) entered the intake hole, the volume of intake air Q_{AIR} can be calculated from the continuity equation:

$$Q_{SF_6} = C_{av}\ T\ Q_{AIR}\ .$$

In this case, Q_{AIR} is the airflow rate, Q_{SF_6} is the volume of SF_6 released, C_{av} is the average SF_6 concentration in the 27 samples containing SF_6, and T is the 27-minute time interval that these samples represent. Therefore:

$$12.2 \text{ liters} = 470 \times 10^{-9} \frac{ft^3\ SF_6}{ft^3\ air} (28.2 \text{ liters}/ft^3)(27 \text{ min})\ (Q_{AIR}),$$

from which we can calculate that Q_{AIR} = 34,000 cfm and the average velocity is about 42 ft/min. This technique is similar to the method used by Higgins and Shuttleworth (6).

Air Exchange Study in End Room on Working Face

At the time these ventilation tests were conducted, 16 room was the end room on the working face (fig. 10). There was an obvious buildup of dust and diesel fumes in this area. It was assumed that the intake air, which was intended to sweep the entire working face, did not reach 16 room in sufficient amounts to clear the dust and fumes. To check this assumption, about 30 liters of SF_6 were released into the intake air in 5 room at 9:45 a.m. (see fig. 10). At the same time, gas sampling was started simultaneously at the junction of 16 room with 10 butt, and in 9 butt about 50 feet downstream from the auxiliary fan located between 13 and 14 rooms. This auxiliary fan is

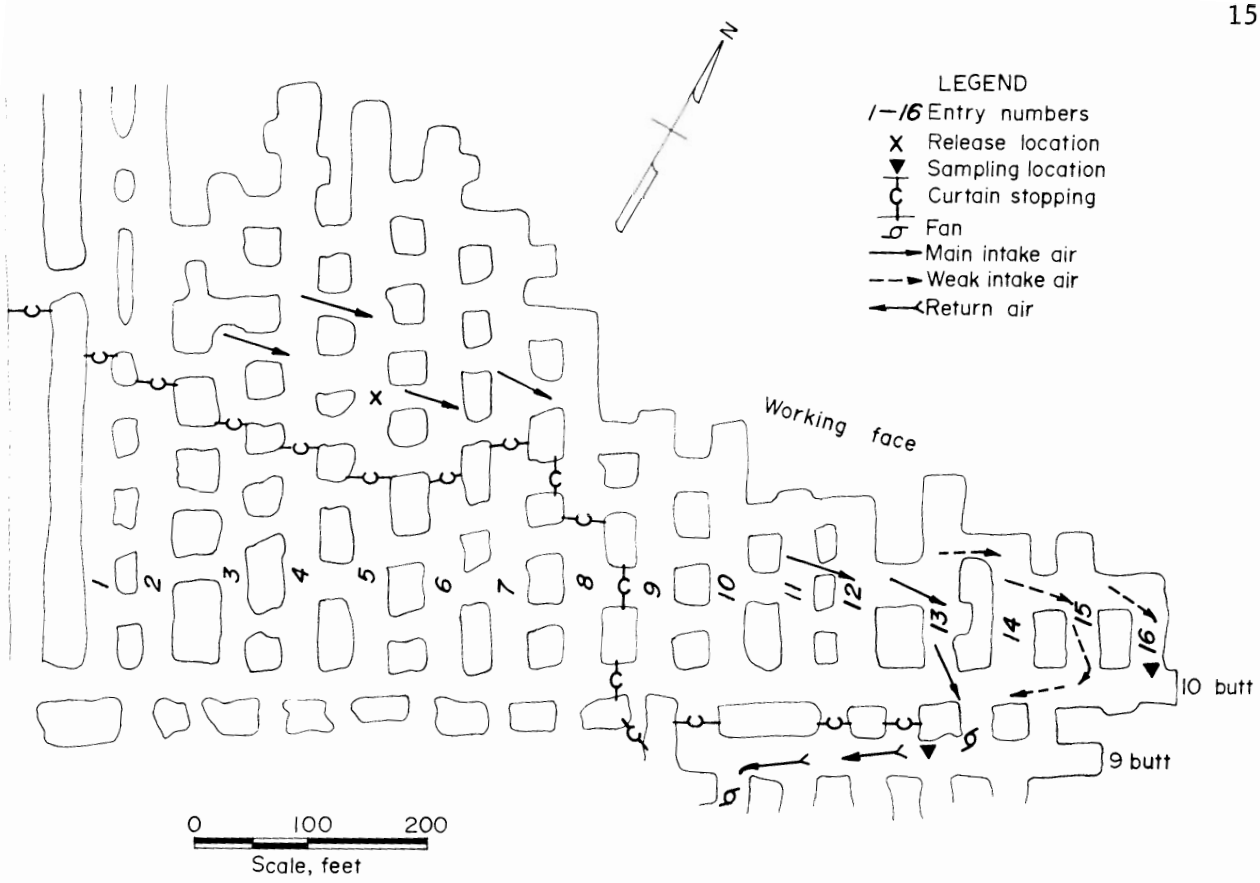

FIGURE 10. - Diagram of air exchange study in 16 room.

intended to exhaust the air from the working area. Samples were taken every minute for 30 minutes.

After 30 minutes, the samples taken in 16 room at 10 butt showed at the most slight traces of SF_6, the concentrations were around 1 ppb. On the other hand, samples taken in 9 butt, downstream from the fan, exceeded 100 ppb SF_6 after 2 minutes of sampling and continued to show these high concentrations throughout the 30 minutes of sampling. Assuming the concentrations in 16 room to be 1 ppb or less, and since the average concentration in the return air in 9 butt was generally greater than 100 ppb, this indicates that only 1 percent or less of the intake air reaches 16 room.

Airflow Check in a Nonworking Area

Figure 11 shows a central portion of the mine with the general intake airflow pattern. Most of the intake air flows along 8 and 9 north entries, but some may circulate around the area of 4-7 north entries. This area is not being mined at present, but because future mining operations are planned, a tracer gas test was run to determine if there was any airflow in 4-7 north entries.

At R1 in 7 north entry, 13.4 liters of SF_6 were released at 4:33 p.m. Gas samples were taken in the intake air at S every 2 minutes from 4:35 until

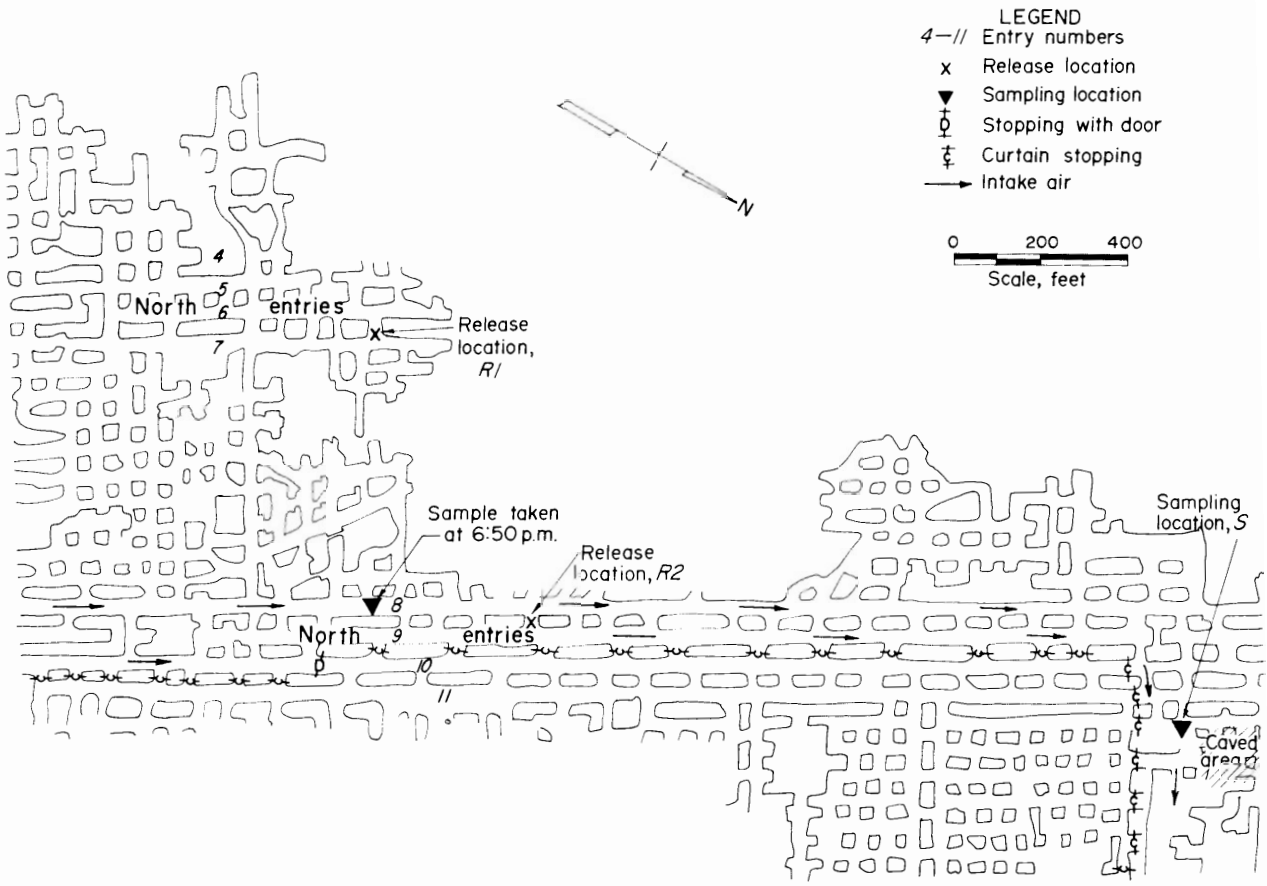

FIGURE 11. - Central portion of the limestone mine.

6:30 p.m. At 6:50 p.m., a gas sample was taken in 8 north entry just below the SF_6 release location in 7 north entry. None of the gas samples showed any evidence of SF_6, indicating that little or no intake air circulated through 4-7 north entries.

Measurement of Airflow in Main Intake Airways

As stated, most of the intake air passes through 8 and 9 north entries. To determine the velocities in these entries, we released 16.8 liters of SF_6 into a crosscut between 8 and 9 entries, at position R2 (fig. 11). The time of release was 7:04 p.m. Samples were taken every minute from 7:04 to 8:00 p.m. at the same sampling location, S, used in the previous test. The distance between R2 and S is about 1,600 feet.

The first sign of SF_6 arrived at the sampling location at 7:17 p.m., 13 minutes after the gas was first released. Dividing the 1,600 feet by 13 minutes gives a maximum velocity of 123 ft/min. Anemometer readings taken in the airway centers in 8 north entry and 9 north entry were 115 ft/min and 121 ft/min, respectively.

If we assume the average velocity to be 0.8 of the maximum velocity, then the average velocity in these airways is 0.8 × 123 ft/min = 98 ft/min.

The continuity equation could not be used to calculate the airflow volume because all of the released SF_6 did not pass the sampling location, as shown in the airflow pattern in figure 11. However, the total intake air volume through 8 and 9 north entries can be estimated. Assuming the combined average cross-sectional area of these two entries to be 1,200 ft^2 and the average velocity to be the calculated 98 ft/min, the intake volume in this area is about 118,000 cfm. Since the volume of air being exhausted from the working areas past the auxiliary fans was found to be only about 47,000 cfm, much of the intake air must be lost through leakage before it ever reaches the working area.

RECIRCULATION TESTS IN A VEIN-TYPE METAL MINE

Recirculation of air from returns into intake airways is a major hazard in many multilevel mines. Usually this results from leakage across old stoped areas. To control recirculation, its origin must be located and the amount of recirculated air measured. SF_6 trace gas can be used for both purposes. Two tracer gas experiments were conducted in a western metal mine, where recirculation was known to occur from the return into the intake (fig. 12). To measure the quantity of return air leaking through the stopes into the intake, a known amount of SF_6 was released into the return air and air in the intake was sampled for a given time. The percentage of SF_6 monitored in the intake should be the same as the percentage of return air recirculating through the stoped areas into the intake. In the first test, 32.4 liters of SF_6 were released into the return air at R1, from 10:45 to 11:00 a.m. The return air rate at this point was 86,000 cfm. At 10:45 a.m., gas sampling every 2 minutes was begun in the intake airway at S1 and continued until 11:41 a.m. The rate here was 87,000 cfm.

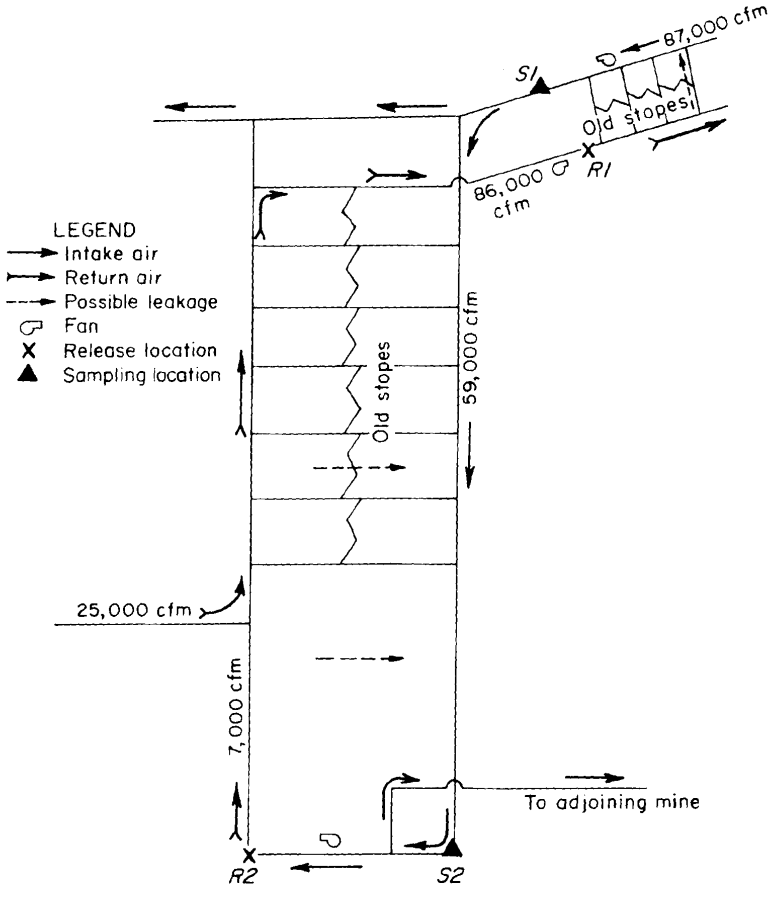

FIGURE 12. - Schematic of recirculation tests in vein-type metal mine.

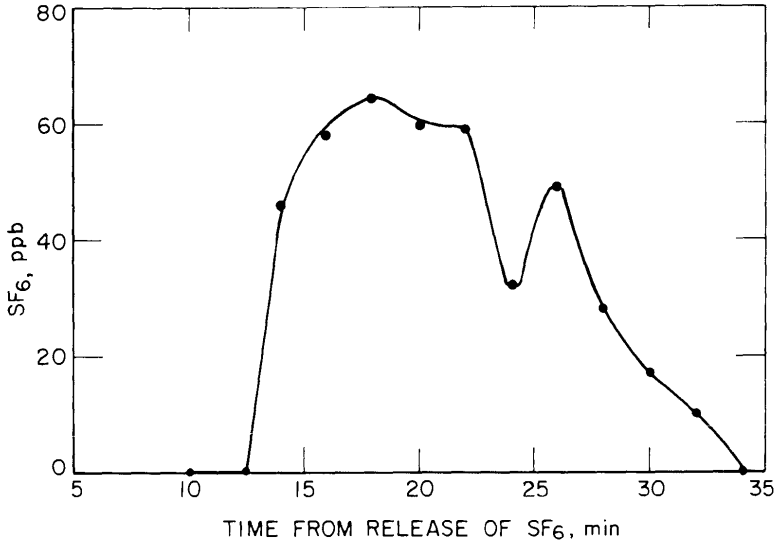

FIGURE 13. - Curve of SF_6 concentration in intake for first recirculation test.

The first SF_6 was detected at S1 at 10:59 a.m. and the last at 11:19 a.m. (fig. 13). A total of 2.1 liters of SF_6 was calculated to have passed S1, making the amount of recirculation in this region slightly over 6 percent.

In the second recirculation experiment, 8.6 liters of SF_6 were released in the return airshaft, at R2, from 1:10 to 1:23 p.m. Sampling began at the bottom of the intake shaft, at S2. Samples were taken every 5 minutes until 2:45 p.m. The intake rate was 58,000 cfm. The return rate was 7,000 cfm at R2, but increased considerably further up the return shaft. Recirculated SF_6 was detected first at 1:40 p.m. and last at 2:30 p.m. (fig. 14). The total quantity of SF_6 recirculated was 5.3 liters, which gives a recirculation of 61 percent. Whether this means that 61 percent of the 7,000 cfm at R2 was recirculated or that 61 percent of some larger volume of return air was recirculated depends upon where the leakage occurred between

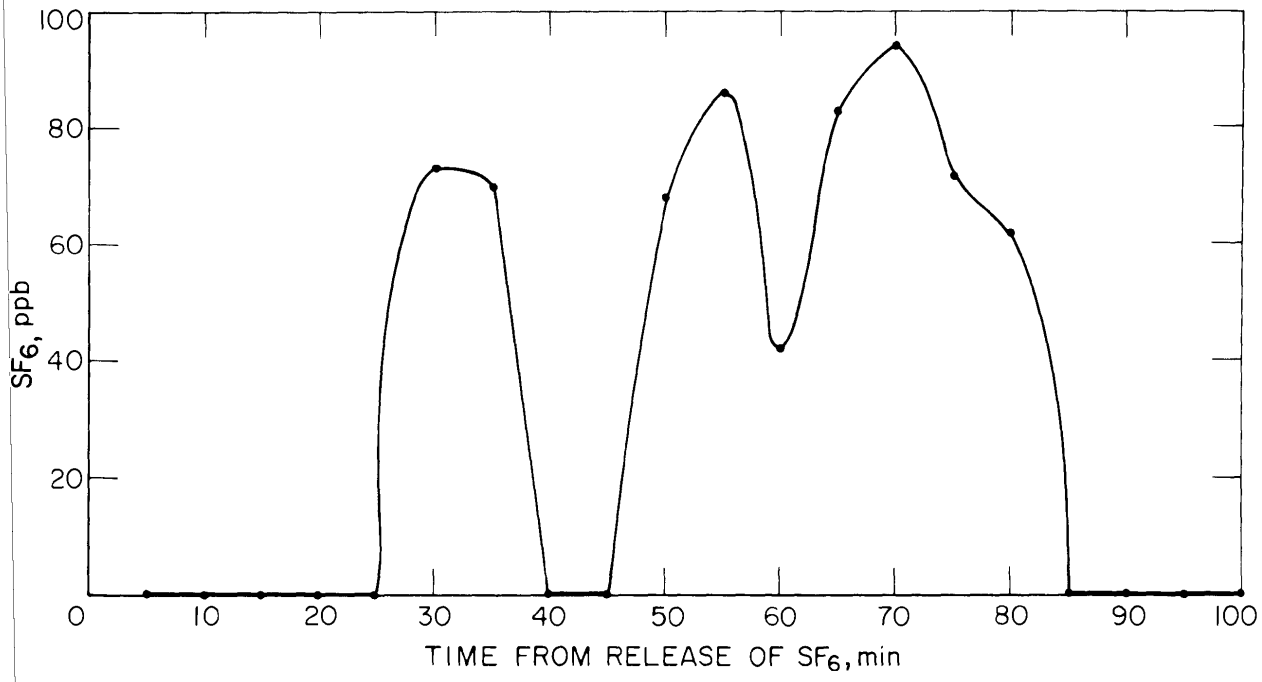

FIGURE 14. - Curve of SF_6 concentration in intake for second recirculation test.

the return and intake airways. If some or all of the leakage occurred above the level where the 25,000 cfm enters the return shaft, then it is 61 percent of the larger air volume. Further tracer gas tests would be required to determine this.

CONCLUSIONS

The SF_6 tracer gas has been shown to be a useful and versatile tool for studying mine ventilation systems. To date, it has been used successfully to measure low velocities (less than 100 ft/min), to determine airflow volumes in airways of large cross-sectional areas (up to 1,000 ft^2), to measure the air exchange rate in areas of little or no airflow, and to measure air recirculation due to leakage across old stopes. Continuing experiments in other types of mines with different ventilation problems will no doubt expand its region of application.

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APPENDIX.--PRELIMINARY TRACER GAS TEST 19

SF_6 was released into the intake air of the mine from 9:01 to 9:06 a.m. The volume of SF_6 released was determined as follows, in grams:

Initial lecture bottle weight = 1328.2,

weight after release = 1266.6;

thus weight of SF_6 released = 61.6

Using PV = NRT where, P = 0.98 atm, T = 300° K, R = 0.082 liter-atm/mole - ° K,

and $N = \frac{61.6 \text{ grams}}{\text{mol wt}} = \frac{61.6 \text{ grams}}{146.07 \text{ grams/mole}}$, we obtain

$$(0.98 \text{ atm})\ V = \frac{61.6 \text{ grams}}{146.07 \text{ grams/mole}} \times \frac{0.082 \text{ liter-atm}}{\text{mole} - ^\circ \text{K}} \times (300^\circ \text{K}).$$

Therefore, V = 10.6 liters of SF_6 released.

Sampling began 3,100 feet downstream from the release point at 9:08 a.m., and continued every 2 minutes until 10:30 a.m. The results from the analyzed air samples are given in table A-1.

TABLE A-1. - Calculation table for test 19

Sample	Time, a.m.	Concentration	Sample	Time, a.m.	Concentration
1	9:08	0	19	9:44	6.6×10^{-7}
2	9:10	0	20	9:46	5.2×10^{-7}
3	9:12	0	21	9:48	4.3×10^{-7}
4	9:14	0	22	9:50	3.2×10^{-7}
5	9:16	6.1×10^{-8}	23	9:52	2.5×10^{-7}
6	9:18	1.0×10^{-7}	24	9:54	2.3×10^{-7}
7	9:20	1.0×10^{-7}	25	9:56	2.0×10^{-7}
8	9:22	1.2×10^{-7}	26	9:58	1.6×10^{-7}
9	9:24	1.8×10^{-7}	27	10:00	1.4×10^{-7}
10	9:26	3.2×10^{-7}	28	10:02	1.3×10^{-7}
11	9:28	7.8×10^{-7}	29	10:04	1.2×10^{-7}
12	9:30	9.5×10^{-7}	30	10:06	9.5×10^{-8}
13	9:32	9.7×10^{-7}	31	10:08	8.2×10^{-8}
14	9:34	1.0×10^{-6}	32	10:10	7.1×10^{-8}
15	9:36	9.6×10^{-7}	33	10:12	6.2×10^{-8}
16	9:38	9.3×10^{-7}	34	10:14	3.6×10^{-8}
17	9:40	8.5×10^{-7}	35	10:16	1.5×10^{-8}
18	9:42	8.5×10^{-7}	36-42	10:18-10:30	Near zero.

Sum of concentrations = $11{,}692 \times 10^{-9}$.

We obtained the average concentration by dividing the sum of column 3 by the number of samples in which a measurable quantity of SF_6 was present. In this case SF_6 was measurable in 31 samples. Therefore, the average concentration was $11{,}692 \times 10^{-9}/31 = 377 \times 10^{-9}$, or 377 ppb.

The anemometer traverse in the return showed an average air velocity of 220 ft/min in a cross-sectional area of 74 ft^2. This results in a volume airflow of 16,280 cfm. Thus, $SF_6 = \left(377 \times 10^{-9} \frac{ft^3\ SF_6}{ft^3\ air}\right)\left(16{,}280 \frac{ft^3\ air}{min}\right)$ $(62\ min)\left(28.2 \frac{liters}{ft^3}\right) = 10.7$ liters

We also obtain 10.7 liters if we use Simpson's rule. Recall that the amount released was 10.6 liters.

A graph of the SF_6 concentration in the return air as a function of time is given in figure 2. The SF_6 concentration in the return built up and slowly dropped off in a smooth manner.

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